NAVAL POSTGRADUATE SCHOOL
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THESIS

SURVIVABILITY DESIGN GUIDELINES
FOR FLY-BY-WIRE FLIGHT CONTROL SYSTEMS DEVELOPMENT

by

Daniel Timothy Hogan

December 1983

Thesis Advisor: R. E. Ball

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Survivability of military combat aircraft has received increased emphasis by the U.S. Armed Services in recent years. The primary objective of the U.S. Military Survivability Policy is to ensure that effective survivability enhancement features are incorporated in current and all future U.S. combat aircraft. Technology advances in Fly-By-Wire Flight Control Systems have significantly enhanced the performance capabilities of modern fighter/attack aircraft. In consonance with the military services survivability policy,

a series of survivability design guidelines for Fly-By-Wire Flight Control Systems have been developed, and are herein presented. A recommendation for future survivability enhancement through the use of digital flight control technology, in a manner similar to artificial intelligence, is presented.

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Survivability Design Guidelines for Fly-By-Wire Flight Control Systems Development

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ABSTRACT

Survivability of military combat aircraft has received increased emphasis by the U. S. Armed Services in recent years. The primary objective of the U. S. Military Survivability Policy is to ensure that effective survivability enhancement features are incorporated in current and all future U. S. combat aircraft. Technology advances in Fly-By-Wire Flight Control Systems have significantly enhanced the performance capabilities of modern fighter/attack aircraft. In consonance with the military services survivability policy, a series of survivability design guidelines for Fly-By-Wire Flight Control Systems have been developed, and are herein presented. A recommendation for future survivability enhancement through the use of digital flight control technology, in a manner similar to artificial intelligence, is presented.

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I. INTRODUCTION

A. COMBAT SURVIVABILITY....A TECHNOLOGY ISSUE

In the skies today and on the drawing boards for tomorrow are military aircraft that are technological marvels. The F-16, and F/A-18 are superior fighter and attack aircraft that employ the very latest in state-of-the-art technologies in computers, flight control systems, engines, and structural materials. These machines have been optimized to levels heretofore unobtainable. Performance has been built-in to these aircraft. And so has something else,.......Survivability. These aircraft were designed to perform their assigned combat missions in the face of modern arsenals and to return to their bases to fly again. However, the question must be asked, have these aircraft designs realized the utmost in survivability benefits that modern digital systems technologies have to offer?

Because history has shown that the importance of survivability has sometimes been forgotten or neglected in the design and development of military aircraft in peacetime, it is incumbent upon the aircaft designer, the military program manager, and the combat aviator to ensure

that today's technological advances, particularly in the application of computer augmented flight control systems, continue to provide the survivability enhancement features that will keep the cutting edge of our nation's defense keen.

B. U. S. MILITARY SURVIVABILITY POLICY

Survivability has been increasingly emphasized by the U.S. Armed Services in recent years. The Department of Defense and the Military Service Branches have established firm survivability policies regarding arms acquisitions. The primary objective of the U.S. Military Survivability Policy is to ensure that effective survivability enhancement features are incorporated in current and all future U. S. weapons systems.

A triservice organization, the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), created in 1971, has brought together the best expertise in each of the service branches to plan and execute a comprehensive program to increase the survivability of current and future aircraft assets. Within the JTCG/AS charter are tasks to develop design criteria and improved technology to increase the survivability of future combat aircraft and weapons systems.

C. SURVIVABILITY REQUIREMENTS/GUIDELINES/STANDARDS

Survivability requirements for airborne weapon systems have been specified in different ways by each branch of the Armed Services. The Navy established AERONAUTICAL REQUIREMENT (AR)-107, "Navy Aircraft Survivability/Vulnerability (Nuclear/Nonnuclear)," in 1974. MIL-STD-2072(AS), "Military Standard: Survivability, Aircraft; Establishment and Conduct of Programs for," superseded AR-107 in 1977. In 1981, The Department of Defense issued MIL-STD-2069, "Requirements for Aircraft Nonnuclear Survivability Programs." Each document was prepared in recognition of the need for a standardized systems approach to improving the survivability of U.S. military aircraft.

DOD MIL-STD-2069 provided guidelines and requirements for establishing and conducting aircraft survivability programs. Applicability of the principles contained therein apply to all major weapons system acquisition programs and is the standard invoked in contractual agreements regarding aircraft armaments.

Various forms of handbooks have been prepared to provide military planners and industrial designers with the

information and guidance needed in incorporating survivability features into new and existing systems. The Air Force Systems Command has published a design handbook series, DH-1 through DH-3 (with supplements) for use with Air Force programs. The Army has publisaed a "Survivability Design Guide for Army Aircraft," USAAMRDL TR-71-41. The Navy established MIL-HDBK-268 (AS), "Survivability Enhancement, Aircraft Conventional Weapons Threats, Design and Evaluation Guidelines," in August 1982 for use in the acquisition process of Naval aircraft systems. Jointly, the three services work within the guidelines established by the JTCG/AS and published in several volumes as DOD-MIL-HDBK-336, "Survivability, Aircraft, Nonnuclear, (Various)."

D. WHY BE CONCERNED WITH AIRCRAFT FLIGHT CONTROL SYSTEMS?

The essential question of flight control survivability was derived by the author from a statement eminating from an analysis of Southeast Asia combat files maintained by the Combat Data and Information Center (CDIC). The statement attributed approximately 25% of all aircraft lost in Southeast Asia to the functional loss of the aircraft's flight control system as a result of combat induced damage.

This percentage figure equated to nearly 500 aircraft. Preliminary investigation revealed that the flight control system of most conventional combat aircraft contributed approximately 5% to the aircraft's total presented area. The disproportionality of the two figures generated a concern that culminated in the development of the guidelines contained herein.

E. PURPOSE

The purpose of this treatise is to present in a single document guidelines for the development of aircraft flight control systems (FCS) with specific emphasis on increasing the combat survivability of aircraft equipped with Fly-By-Wire (FBW) flight control systems.

F. SCOPE

The scope of this effort was limited to nonnuclear weapons effects considerations. The Fly-by-Wire flight control systems development guidelines presented within were developed in connection with the damage causing mechanisms associated with conventional weapons systems, self generated electromagnetic interference (EMI) phenomena, and normal inflight environmental/meteorological conditions to be expected in the combat aircraft's operating environment.

II. FUNDAMENTAL SURVIVABILITY CONCEPTS

A. WHAT IS AIRCRAFT COMBAT SURVIVABILITY?

Aircraft combat survivability has been defined as "the capability of an aircraft (weapon system) to avoid and/or withstand a man-made hostile environment" [Ref. 1]. Paramount in this definition is the ability "to avoid and/or withstand." The inability "to avoid," the hostile environment is referred to as susceptibility. The inability "to withstand," the hostile environment is referred to as vulnerability.

Susceptibility, often measured as the probability of being hit, Ph, can be divided into three general categories:

(1) Defensive weapon system threat activity

(2) Detection, identification, and tracking by defensive weapon systems

(3) Engagement by defensive weapon systems (i.e., missile launch or gun firing; warhead guidance; warhead impact or detonation)

The susceptibility of an aircraft can be influenced by the aircraft's signatures, the tactics and supporting forces employed, and the integral survivability enhancement equipment carried on or within the aircraft. Small size,

increased maneuverability, low visual/radar/aural/infrared signatures, terrain masking/terrain following tactics, active/passive electronic countermeasures, decoys, and antiradiation missiles are but a limited selection of the means to reduce an aircraft's susceptibility.

Vulnerability, often measured as the probability of being killed if hit, Pk/h, is a direct function and measure of the aircaft's design, and any survivability enhancement feature that reduces the amount and effect of damage induced by an enemy's weapon systems damage mechanisms. Vulnerability is influenced by the ability of a system to continue to operate after being hit and by design features and equipment that prevent or suppress damage. A flight control system that continues to function after sustaining a hit by a damage mechanism on one of its components is an example of reduced aircraft vulnerability.

B. SURVIVABILITY ENHANCEMENT CONCEPTS

Survivability enhancements have been generally categorized as any feature of an aircraft, any equipment carried, any tactic employed, or any combination thereof that reduces the susceptibility and/or the vulnerability of an aircraft. Survivability enhancements can be separately

concentrated into either susceptibility reduction features or vulnerability reduction features. Those specific susceptibility and vulnerability reduction features can be summarized generically into conceptual elements. The first of the two categories relating the major survivability enhancement concepts is listed in Table I.

TABLE I

Survivability Enhancement Concepts - Susceptibility Reduction

(1) Signature Reduction

(2) Warning Receivers

(3) Electronic Countermeasures Devices

(4) Expendables

(5) Tactics

(6) Threat Suppression

As presented in Table I, a reduction in an aircraft's susceptibility can be brought about by decreasing its detectability through signature reduction. Reducing an aircraft's ability to be detected and tracked by an enemy can best be accomplished in the design process. Incorporation of quieter, smokeless engines, utilizing radar

absorbent materials, eliminating sharp edges (corner reflectors), and prescribing low IR reflective paint schemes are examples of this technique. Alerting the crew to impending missile or gun activity can be achieved through the use of appropriately selected warning receivers. Incorporating electronic countermeasures devices, such as noise jammers and deception repeaters, can degrade or prevent an enemy's defensive systems ability to achieve a suitable weapons firing solution. Expendables, in the form of chaff, infrared flares, and off-board decoy devices, can confuse and degrade an enemy's weapon systems by masking an aircraft's true identity or location. Minimization of exposure to an enemy's defensive network can be achieved through a suitable selection of tactics alternatives. Examples of this technique can be found in operational plans that take advantage of terrain following/terrain masking flight profiles and that utilize stand-off or launch-and-leave weapons. The impact of crew skill and experience and the increased performance capabilities of the modern fighter/attack aircraft, brought about, in part, by the incorporation of FBW flight control systems technology, can have a major impact on tactics selection. Threat

suppression, the ability to actively deny the enemy an unhindered opportunity to fire his weapons, can be achieved by attacking his weapons emplacements with such means as anti-radiation missiles and coordinated supporting fire from ancillary units.

The six concepts described above comprise susceptibility reduction, the avoidance portion of the survivability dual. Completing the dual are six vulnerability reduction concepts. These six complementary concepts are presented in Table II.

TABLE II

Survivability Enhancement Concepts - Vulnerability Reduction

(1) Component Location

(2) Component Shielding

(3) Component Redundancy

(4) Component Elimination

(5) Passive Damage Suppression

(6) Active Damage Suppression

Vulnerability reduction can be best achieved in the design phases of an aircraft's development. Judicious selection of the location of critical components to minimize

the possibility of damage and shielding those critical components to prevent damage mechanisms from striking the components, rendering them unservicable, are techniques most suited to be achieved during the early design phases. Incorporation of more than one component to perform a critical function (component redundancy) can have a major impact on the vulnerability of an aircraft or aircraft system. Additional reductions may be achieved through the elimination of components entirely (component elimination). Passive and active damage suppression reduces aircraft vulnerability either by controlling the effects of damage mechanisms or by reducing or preventing the subsequent spread of further damage causing effects.

Suitable attainment of an appropriate level of aircraft survivability can be achieved through the incorporation of elements from each of the survivability enhancement concepts described. However, it must be noted that not all survivability enhancement concepts are necessary or appropriate for any particular aircraft type on any particular mission. Paradoxically, a reduction in vulnerability may lead to a greater degree of susceptibility, such as the case faced by the designer when

adding large amounts of armor plate to an aircraft, thereby increasing the ability to tolerate a hit, but making the aircraft more susceptible to being hit by reducing its speed. Consequently, the early identification and successful incorporation of those survivability enhancement features that most significantly increase the survivability of the aircraft's flight control system and increase the mission effectiveness of the combat aircraft as a weapons system is to be regarded as a goal of the survivability discipline.

III. FLIGHT CONTROL SYSTEMS

A. FLIGHT CONTROL BASICS

Flight path control of an aircraft is accomplished by means of a complex series of electrical, hydraulic, and mechanical devices collectively titled the flight control system (FCS). These basic elements, when transformed into sensors, signal paths, actuators, and surface panels, provide the means by which the pilot commands an aircraft in-flight about the three axes of motion.

Conventional military aircraft utilize three primary control surfaces to control the three dimensional motion of the aircraft: the elevators, the rudder and the ailerons. A right-hand orthogonal axis system and the motions produced by the associated control surfaces are illustrated in Figure 3.1.

Deviations from the basic control surfaces are functions of the geometric shape of the aircraft. In some aircraft configurations, the elevators are replaced by a solid horizontal tail, designated either a stabilator or stabilizer by the manufacturer, which moves as a single unit to provide pitch control. In some aircraft, the tail surfaces can be controlled either symmetrically or

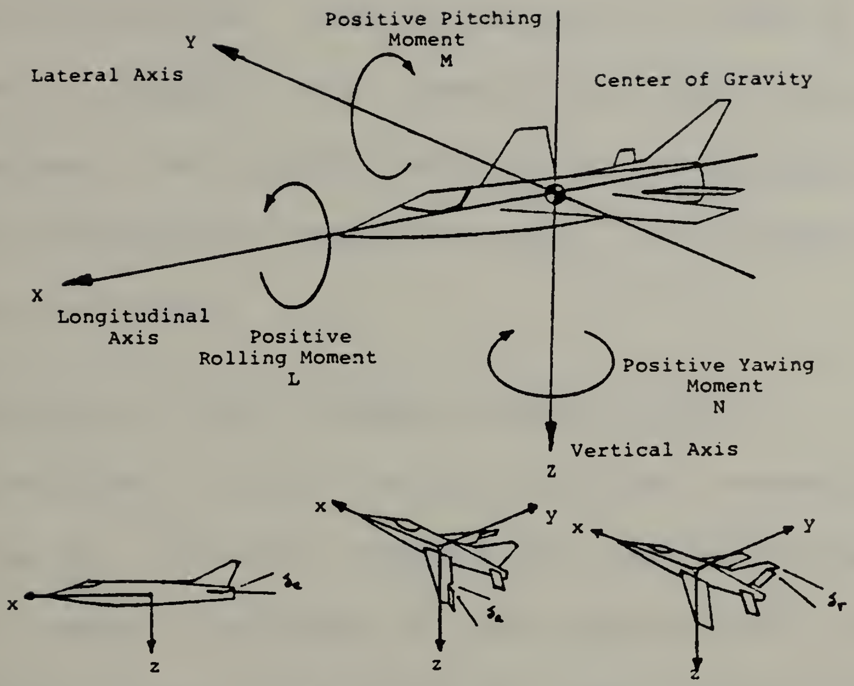


Figure 3.1. Reference Axes/Control Surface Deflections

assymmetrically to provide pitch and roll control. This type of tail surface is known as a differential stabilator. Tailless aircraft employ elevons in place of ailerons and elevators to provide pitch and roll control. Flaperons replace ailerons in still other designs.

Additional surfaces, such as speedbrakes, spoilers, leading and trailing edge flaps, and leading edge slats, are

classified as secondary or auxiliary control surfaces. These devices provide an aircraft a means of speed and direct lift control, and can be used as back-up control surfaces. Despite the nomenclature and physical differences, the primary function of a particular control system configuration remains to guide the aircraft in three dimensional flight.

B. MECHANICAL FLIGHT CONTROL SYSTEM BASICS

Conventional flight control surface movements are commanded by the pilot through the control column and control pedals. Movement of the elevator and ailerons is commanded by means of a stick or wheel controller, and movement of the rudder is prescribed by a pair of rudder pedals. The basic mechanization scheme is illustrated in Figure 3.2. The control column and rudder pedals are mechanically linked to the control surfaces by cables, pushrods, and bellcranks as illustrated in Figure 3.3 for a longitudinal control system.

C. POWER-ASSISTED CONTROL SYSTEM BASICS

Most high speed military combat aircraft require some form of powered flight control system to give the pilot adequate control of the aircraft throughout the flight

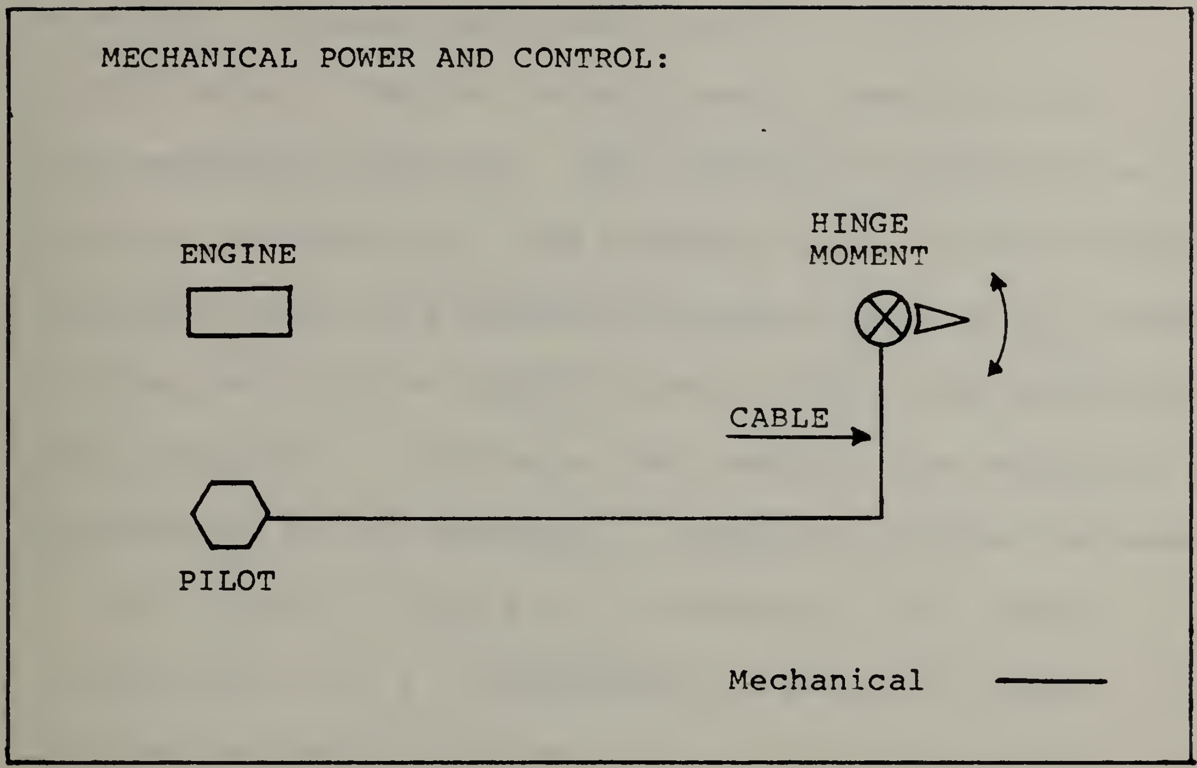


Figure 3.2. Mechanical Flight Control Mechanization

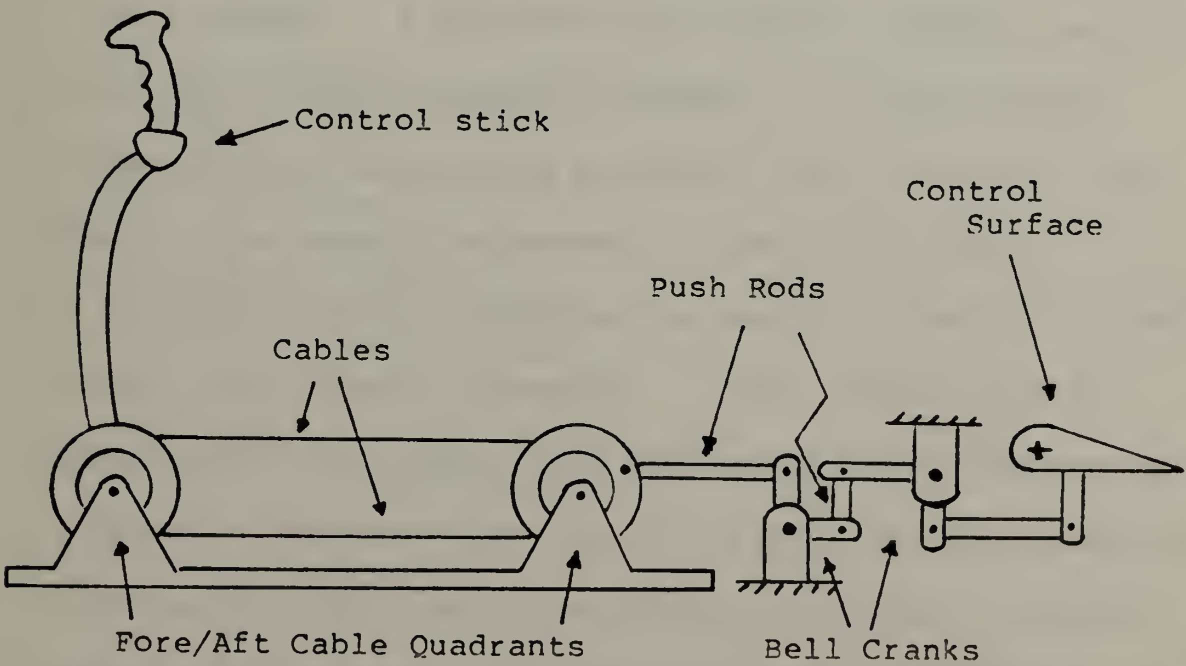
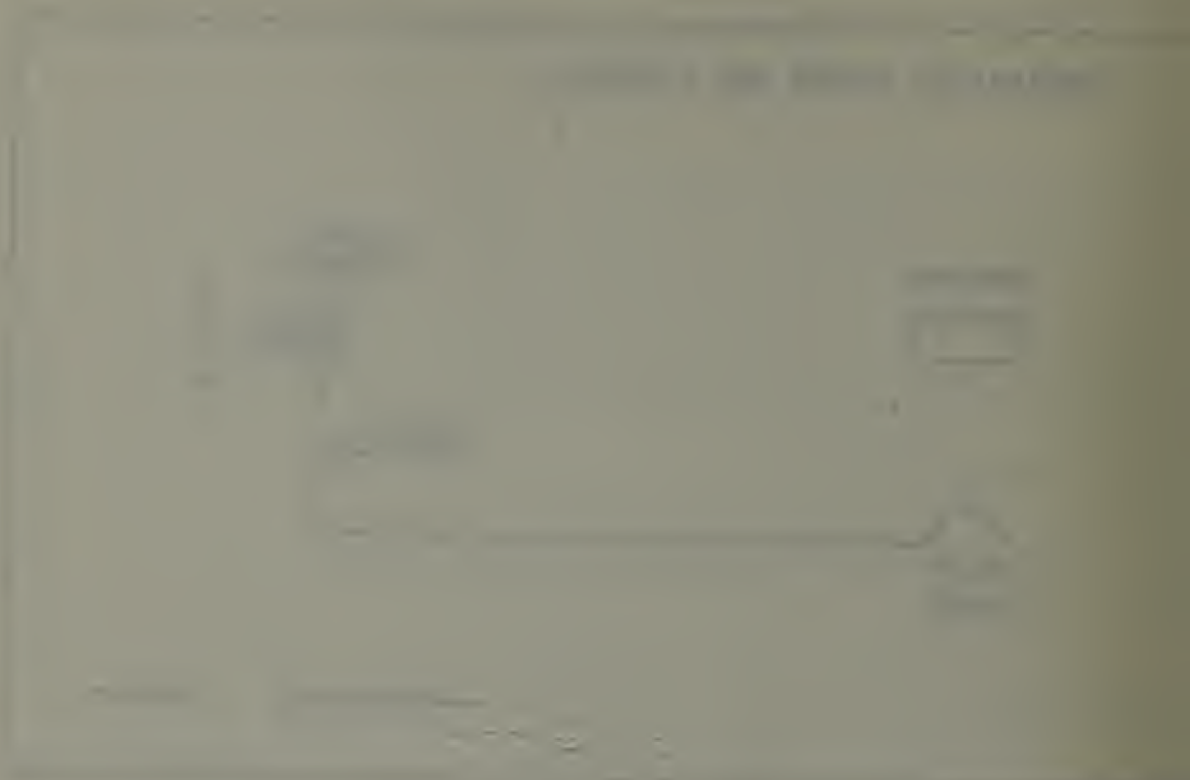
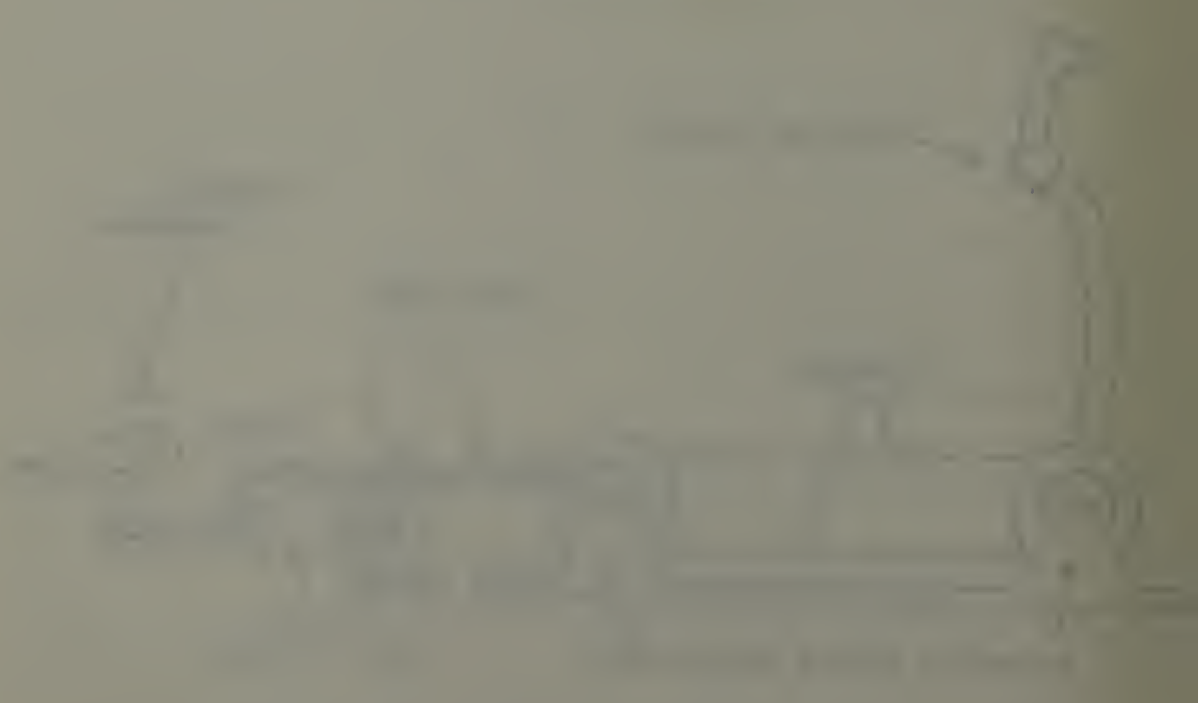


Figure 3.3. Mechanical Longitudinal Control System





envelope. Conventional power-assisted control system designs usually derive the additional power by means of hydro-mechanical devices. The fundamental configuration is depicted in Figure 3.4. The hydraulic pump, selector valve, servoactuators, and associated plumbing, while adding weight and complexity to the control system, provide the additional power required. Artificial feel devices are generally incorporated in the mechanical linkage to provide feedback to the pilot. Figure 3.5 illustrates the basic mechanization of a conventional hydraulic powered longitudinal control system.

D. FLY-BY-WIRE (FBW) CONTROL SYSTEM BASICS

Many modern, high technology combat aircraft employ fly-by-wire flight control systems. In the basic configuration, illustrated in Figure 3.6, the pilot is linked to the control actuators by electrical wires. The electrical wiring provides the control signal paths that transmit the pilot's commands to the servoactuators. Sophisticated artificial feel devices provide feedback to the pilot. The basic FBW control system configuration is electrically noisy, and the aircraft is prone to pilot induced oscillations. To aid in the controllability of the

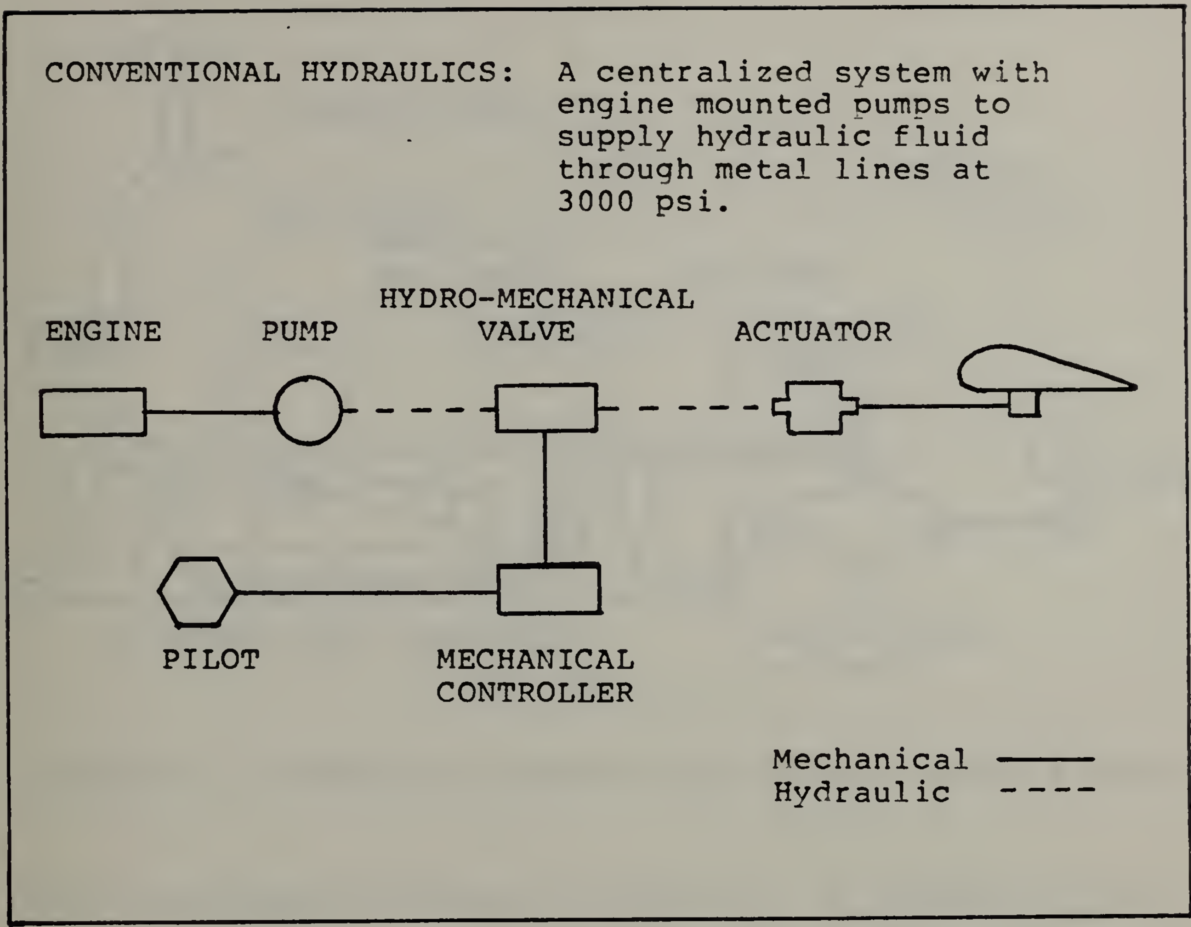
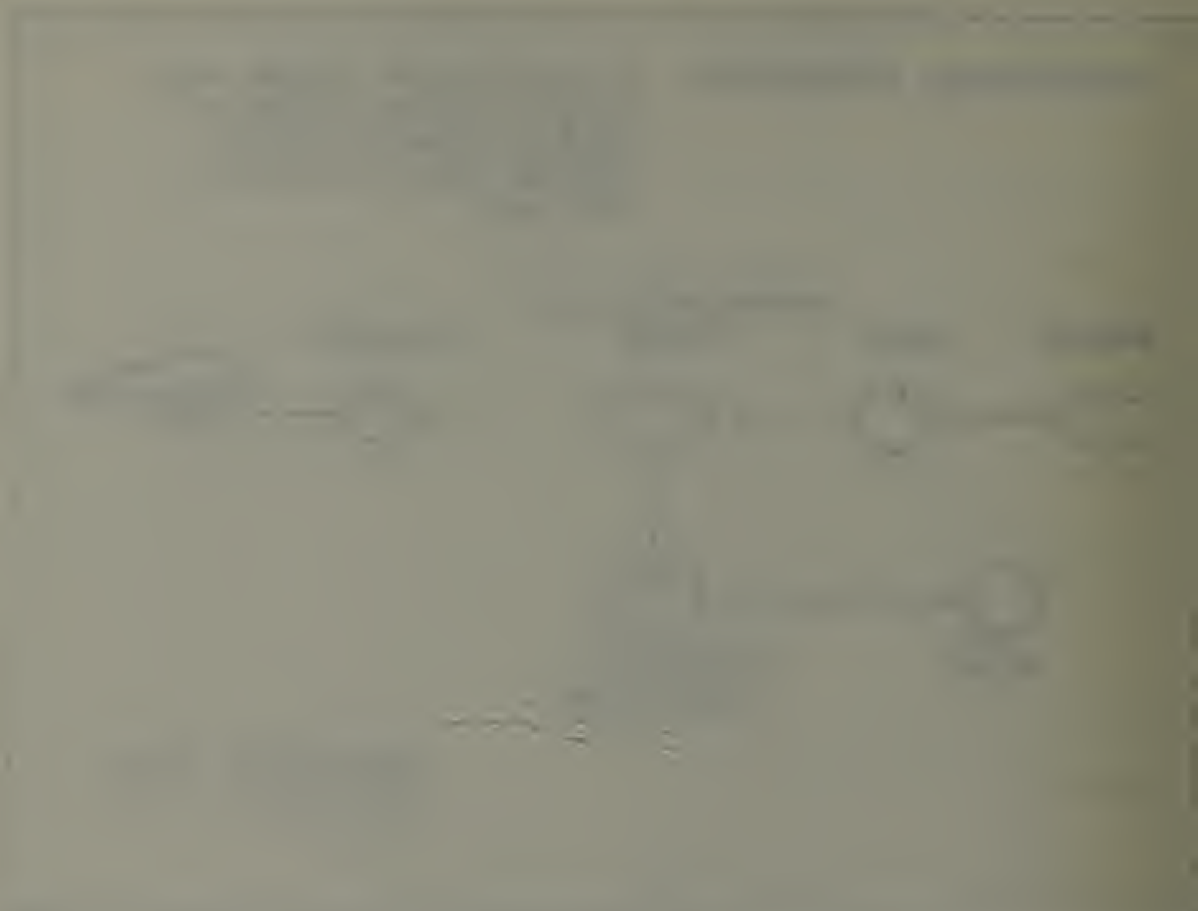


Figure 3.4. Hydraulic Power System Mechanization

aircraft, a series of electronic filters is often inserted in the system between the pilot and the electro-mechanical selector device to reduce noise transients.

E. COMPUTER AUGMENTED FBW CONTROL SYSTEM BASICS

High speed computers, in-line with the basic FBW flight control system, may be used to either augment or provide the controllability of the aircraft. Computer monitoring of the



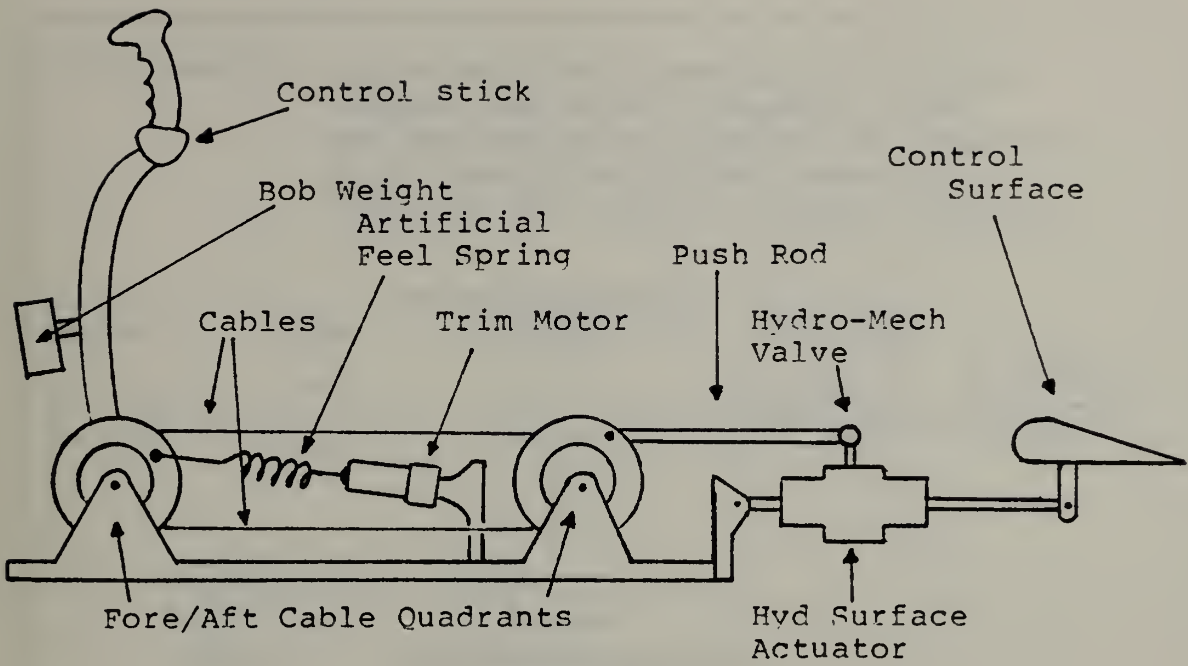


Figure 3.5. Hydraulic Powered Longitudinal Control System

flight environment through the addition of motion and rate sensors coupled to the computer relieves the pilot of the responsibility to continuously monitor his flight path.

One of the most sophisticated applications of a digital computer augmented FBW flight control system in a military combat aircraft is the McDonnell-Douglas F/A-18 "Hornet." This aircraft employs high speed digital computers in-line with a state-of-the-art FBW system to provide the very latest in high performance aircraft flight control systems technology.

FLY-BY-WIRE: The conventional mechanical linkage between the pilot's control input and mechanical controller is replaced by an electrical signal used to activate the control surface actuator.

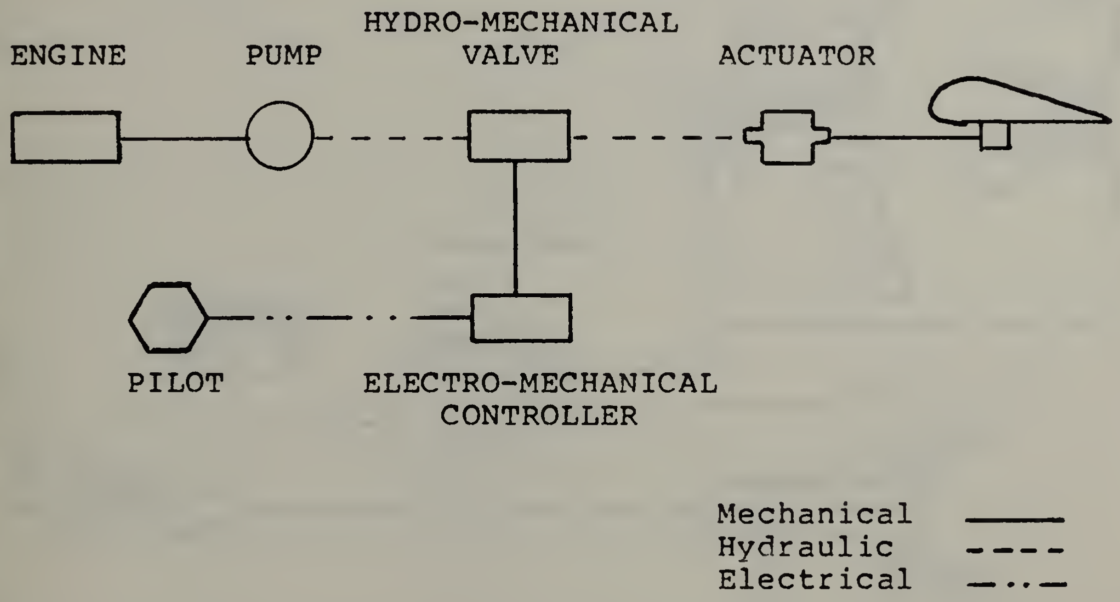


Figure 3.6. Fly-by-Wire Control System Mechanization

The functional design of the F/A-18 Digital Fly-by-Wire (DFBW) flight control system is illustrated in Figure 3.7. The basic mechanical and electrical FCS subsystems are diagrammed in Figure 3.8. The basic hydraulic FCS subsystems are depicted in Figure 3.9. Note the mechanical back-up components for controlling the pitch and roll motion of the aircraft.

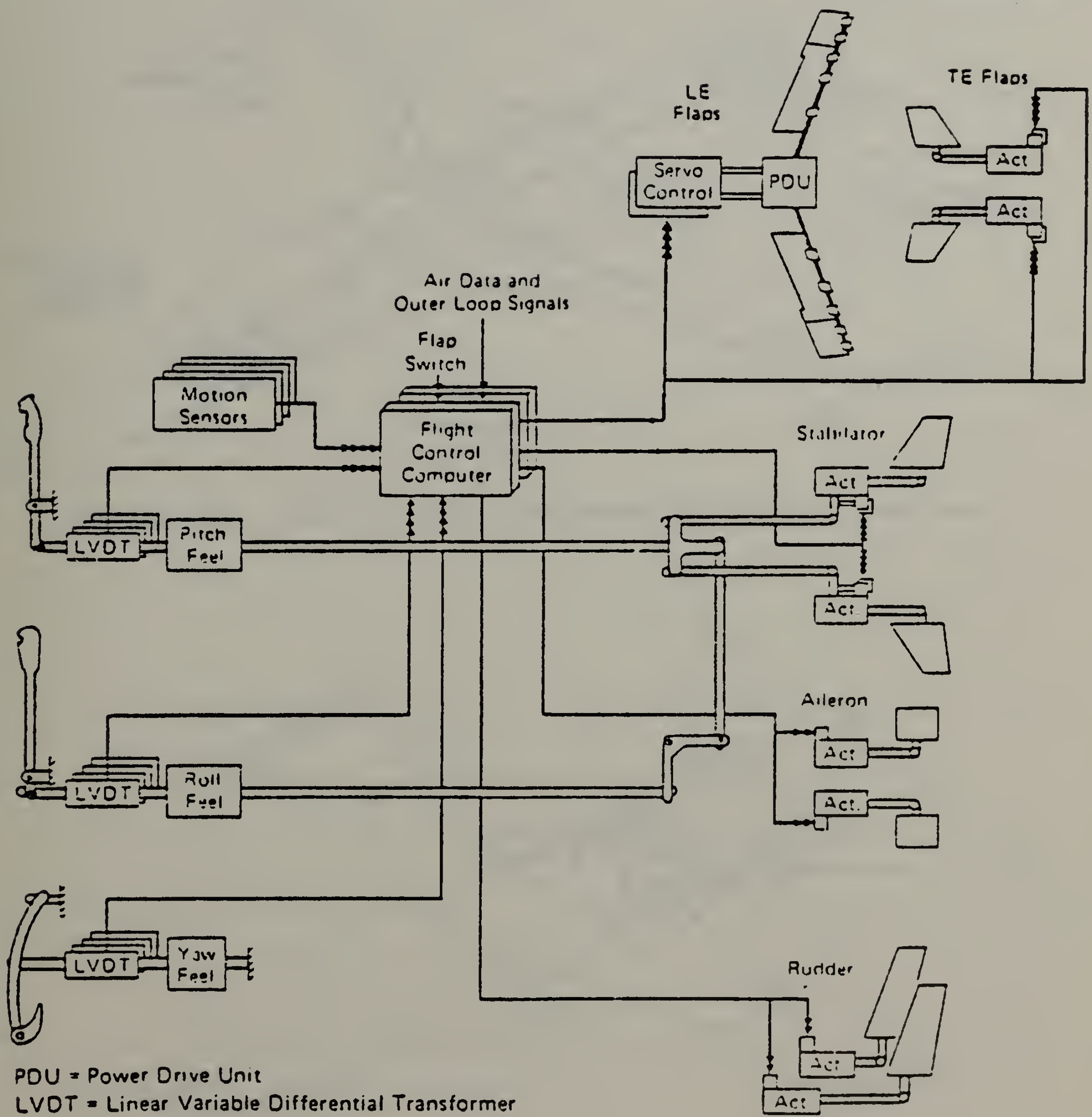
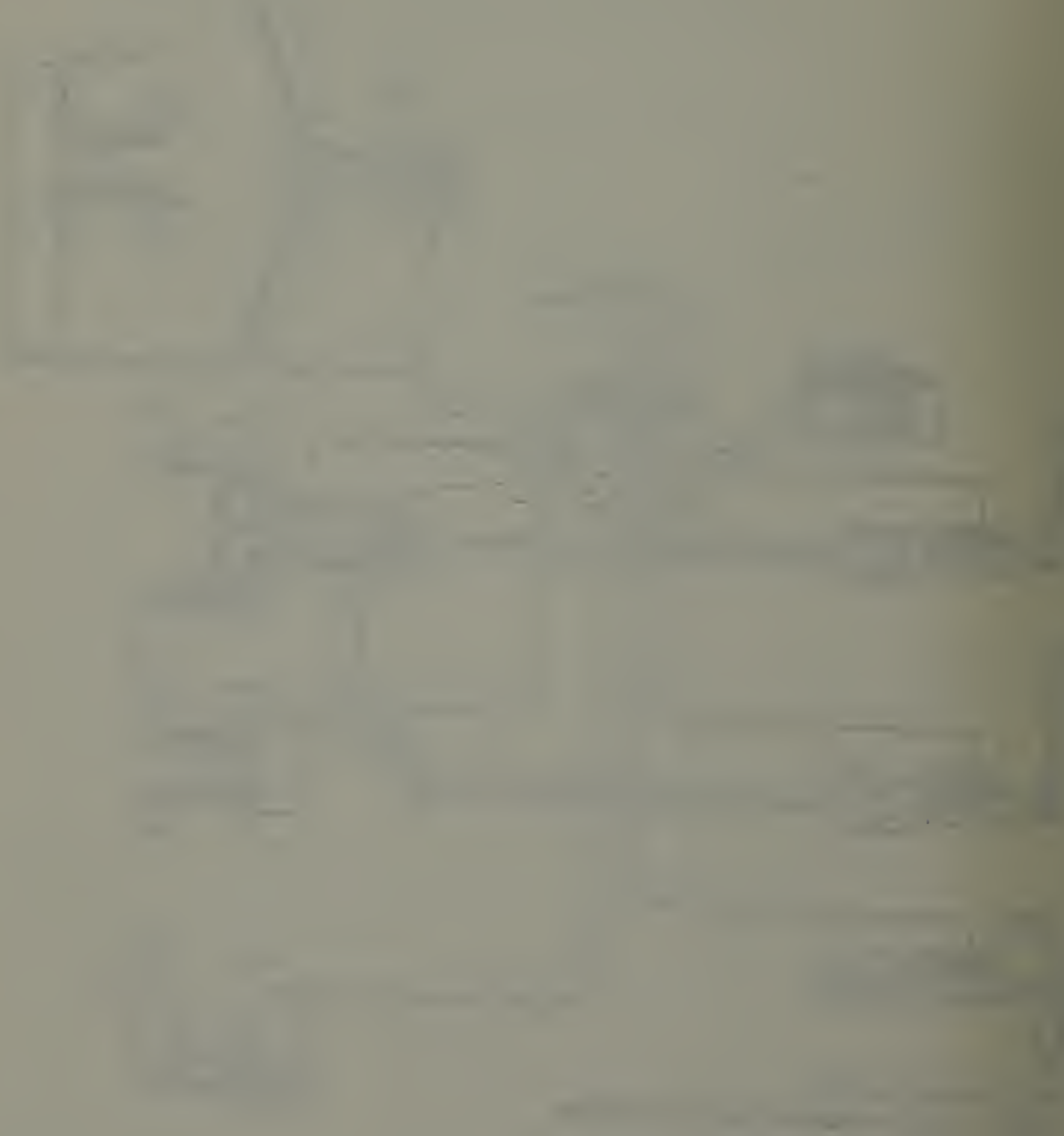


Figure 3.7. F/A-18 FCS Functional Diagram



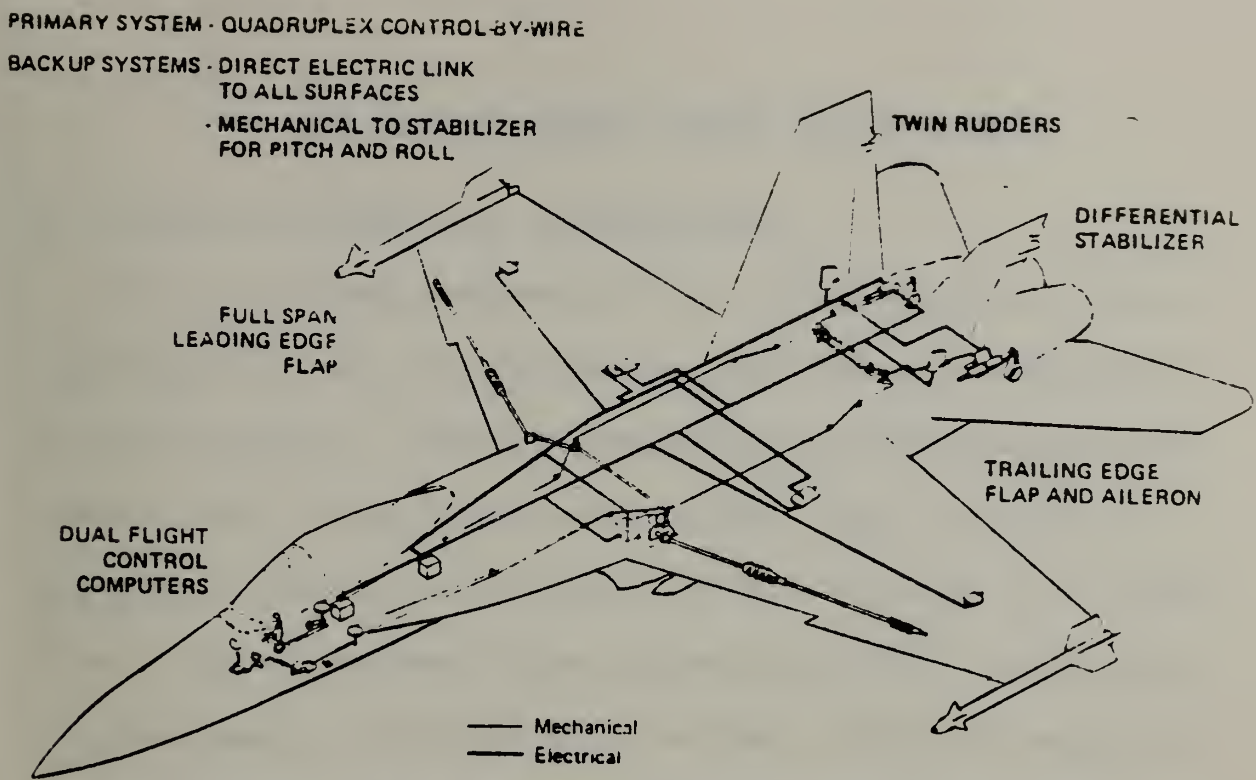


Figure 3.8. F/A-18 FCS Elec/Mech Subsystem Diagram

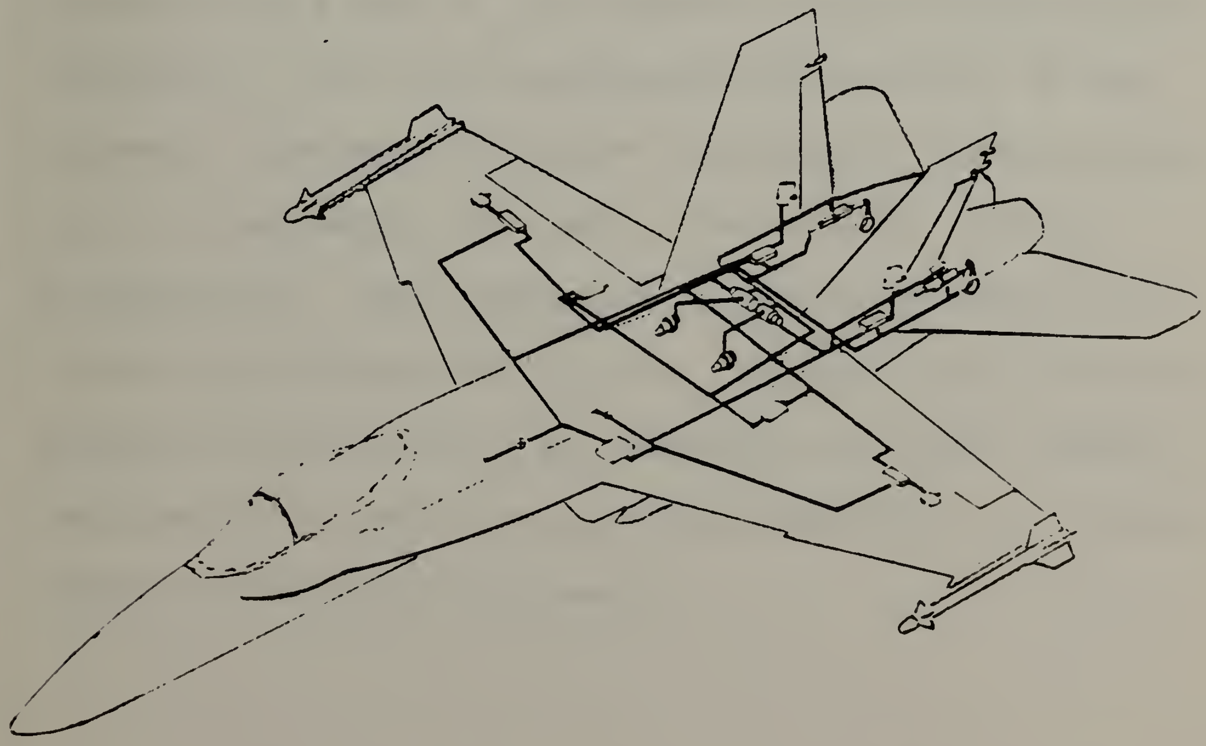


Figure 3.9. F/A-18 FCS Hydraulic Subsystem Diagram

IV. FCS FAILURE/DAMAGE MODES IDENTIFICATION

A. SYSTEM VULNERABILITY CONTRIBUTIONS

Each individual component of an aircraft has a level of vulnerability that contributes to the overall vulnerability of the aircraft. Certain components contribute more than others, and those components which, when damaged or destroyed, lead to an aircraft loss are the ones of interest here. These components are known as critical components. The systemmatic identification of the critical components and the quantification of the vulnerability of individual components is a part of the overall aircraft vulnerability assessment. As the vulnerability contribution of each component, subsystem and system is assessed, various methods may be implemented to reduce the overall aircraft vulnerability. The vulnerability reduction technique(s) chosen for implementation in the FCS must allow the FCS design to remain within the constraints of cost, weight, performance, accessibility, and maintainability, et cetera imposed by contractual agreement.

B. IDENTIFICATION OF CRITICAL COMPONENTS

One purpose of a vulnerability assessment is the identification of those components whose damage or loss could lead to an aircraft kill. A general procedure has been formulated for determining the critical components, their possible damage or failure modes, and the effects of the damage or failure on the continued operation of the aircraft [Ref. 1].

Fundamentally, the procedure is comprised of three steps:

(1) selection of an aircraft kill level.

(2) formulation of a complete technical and functional description of the aircraft.

(3) the identification and delineation of the critical components.

1. Aircraft Kill Levels

Combat damaged aircraft and aircraft systems suffer performance degradations in varying degrees. The level to which the performance degradation progresses can, in general, be categorized as an attrition kill, a mission abort kill, or a forced landing kill.

An attrition kill is defined as that measure of aircraft damage that results in the loss of the aircraft from the inventory. Repairability and economy of repair are factors which may contribute to to an attrition kill without the physical loss of the aircraft. However, it is the elapsed time from damage onset to eventual aircraft loss which provides the scale with which to differentiate between attrition kill levels. Several attrition kill levels have been defined; such as "KK", "K", "A", and "B", impressed on a time to aircraft loss scale. Detailed kill level descriptions are contained within DOD MIL-STD-336-1 [Ref. 2].

A mission abort kill is defined as that measure of aircraft damage which results in an aircraft failing to complete its assigned mission, but that does not result in a loss of the aircraft from the inventory.

A forced landing kill, specifically applicable to helicopters, VTOL, and certain V/STOL aircraft, is defined as that measure of aircraft damage that causes the pilot to land his aircraft short of the intended destination, and the failure to do so would result in the destruction of the aircraft.

2. Aircraft Technical and Functional Description

At each successive stage of the aircraft design process, the technical and functional descriptions of aircraft systems and components become better defined. These descriptions, with individual component and systems dimensions, materials, operations and functions interfaces, scale and perspective drawings, and aircraft location profiles, comprise the detailed technical base for use in the vulnerability assessment. Gathering and continuously updating this data base, as it is formulated, should be given a very high priority.

3. Critical Component Identification Procedure

A sequenced procedure has been formulated to identify the critical components [Ref. 1]. The first step in this analysis procedure for the FCS is to identify the flight essential functions that the FCS must perform in order to continue to accomplish the aircraft's mission. The second step is to identify those FCS subsystems and components that provide or perform the essential functions. The third step is to conduct a failure mode and effects analysis (FMEA) and/or a fault tree analysis (FTA) to identify the relationship between the individual component

or subsystem failure and the essential function(s) it provides or performs. The fourth step, the damage modes and effects analysis (DMEA), consists of relating the component or subsystem failure modes to combat damage causes. The final step in the process, the presentation of the results, is often expressed in a logical sequence known as a kill expression, or represented graphically as a kill tree.

4. Procedural Example - Generic DFBW FCS

To illustrate this dynamic process, the flight control system of a generic fighter/attack aircraft will be utilized. The time scale of a "B" level attrition kill will be imposed for illustrative purposes.

A schematic representation of the example DFBW FCS layout is shown in Figure 4.1. Specific technical and functional interfaces are depicted in Figure 4.2. The FCS utilizes dual, high speed digital computers, quadruple transmission signal paths, two independent hydraulic systems, and dual, tandem hydraulic actuators at all control surfaces. No back-up mechanical control linkage is provided.

Flight essential functions are those that are required to sustain controlled flight with qualities not

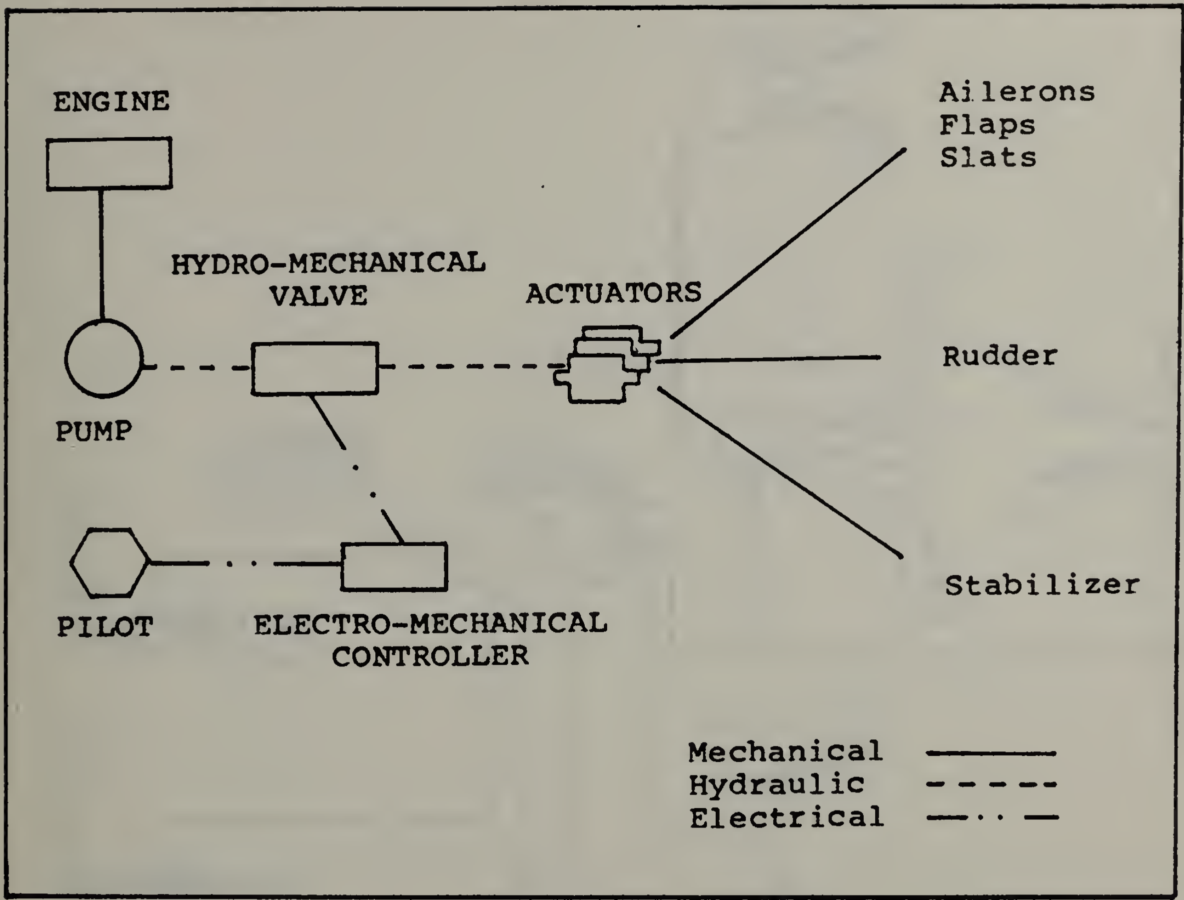


Figure 4.1. Generic DFBW FCS Illustration

less than level 3 as defined by MIL-F-8785C [Ref. 3]. Each mission phase constitutes an evaluation point in the process. Mission phases for a typical multipurpose fighter/attack aircraft include takeoff, climb, outbound cruise, descent, target ingress, ordnance delivery, target egress, climb, inbound cruise, descent, and landing, as shown in Figure 4.3. Figure 4.4 delineates those flight essential functions in a typical format for the example fighter/attack aircraft.

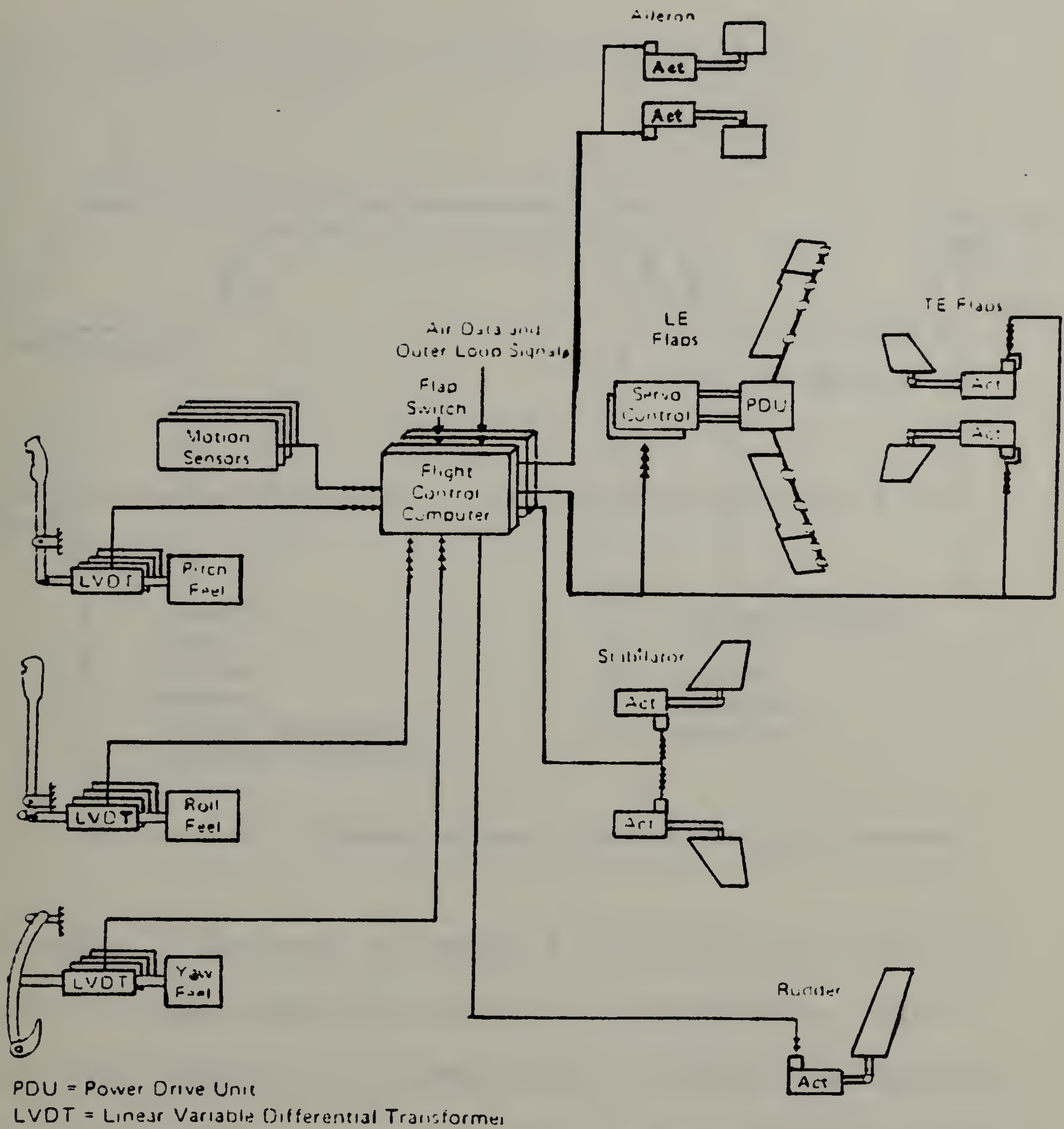
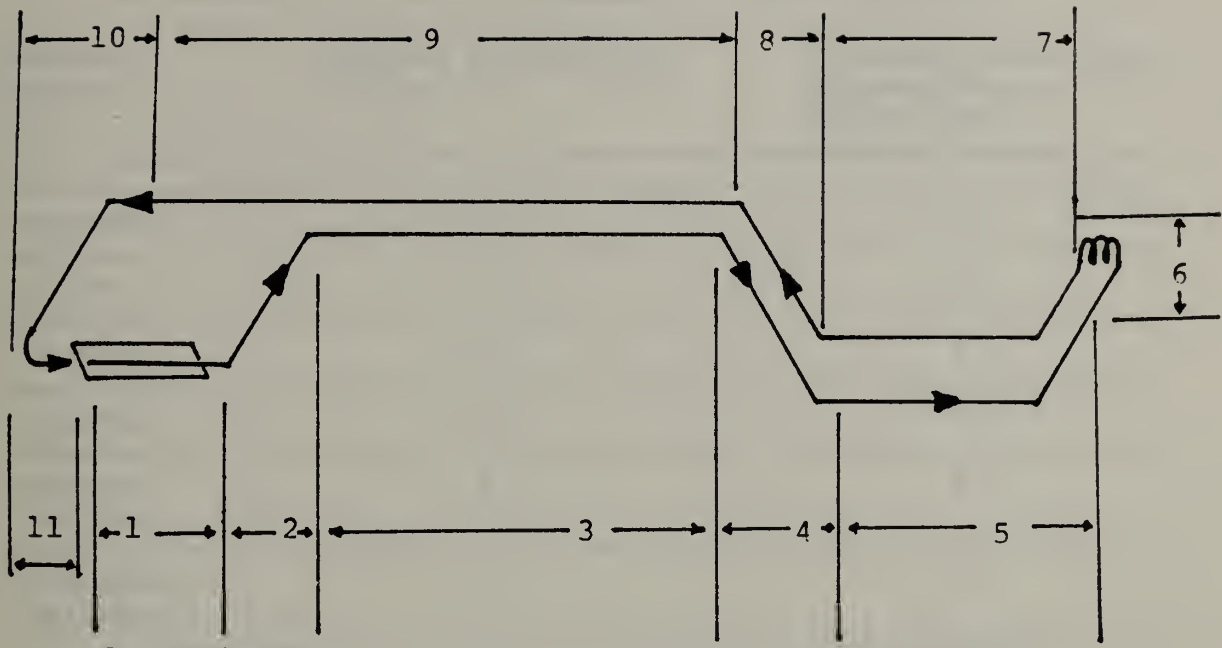


Figure 4.2. Technical/Functional Interfaces - DFBW FCS

To fly and conduct the aircraft's mission requires the continued operation of those supporting systems or subsystems that provide or perform the essential FCS



1. Takeoff
2. Climb
3. Cruise
4. Descent
5. Target Ingress
6. Ordnance Delivery
7. Target Egress
8. Climb
9. Cruise
10. Descent
11. Landing

Figure 4.3. Fighter/Attack Mission Profile Phases

function. The level of severity and time criticality of loss of these supporting systems or subsystems must be evaluated during this process step. Figure 4.5 depicts a sample tabulation of some of those major supporting systems and subsystems. In depth and detailed analyses of each individual supporting element must be carried out as each of these elements becomes sufficiently defined during the design process. A sample tabulation of a more detailed analysis is presented in Figure 4.6.

Mission Phases	Essential FCS Functions: Provide Controlled Flight	Essential FCS Functions: Provide Continuous System Status Monitoring
Takeoff	X	X
Climb	X	X
Cruise	X	X
Descent	X	X
Target Ingress	X	X
Ordnance Delivery	X	X
Target Egress	X	X
Climb	X	X
Cruise	X	X
Descent	X	X
Landing	X	X

Figure 4.4. FCS Essential Functions vs. Mission Phases

Continuously updating the technical and functional data base provides the basis and means for further refinements of the detailed supporting systems analysis.

The third phase in the analysis procedure is the failure mode and effects analysis and/or the fault tree analysis. The FMEA is a "bottoms-up" procedure that

Supporting System/Subsystem Functions	Essential FCS Functions: Provide Controlled Flight	Provide Continuous System Status Monitoring
Electrical Power	X	X
Hydraulic Power	X	
Airconditioning/ Environmental Control	X	
Motion Sensor Input	X	

Figure 4.5. Basic Systems/Subsystems Supporting The FCS.

identifies all possible failure modes of a component or system, documents these failure modes, and determines the effect of each failure mode on the performance of the system as a whole. The details of the FMEA process, and specific procedures can be found in MIL-STD-785 [Ref. 4].

Component failure modes generally considered in an FMEA include failure to operate, failure to terminate

Detailed Supporting System/ Subsystem Functions	Essential FCS Functions: Provide Controlled Flight	Essential FCS Functions: Provide Continuous System Status Monitoring
Generate AC/DC Elec Power	X	X
Distribute AC/DC Elec Power	X	X
Provide Auto Elec Ctc Protect	X	X
Provide Battery Power	X	X
Generate Hydraulic Power	X	X
Distribute Hydraulic Power	X	X
Provide Hyd Fluid Level Sensing	X	X
Provide Aircond/ Environ Ctc Protection	X	X
Provide Continuous Transmission Signal Path	X	X
Provide Continuous Sensor Input	X	X

Figure 4.6. Detailed Support Systems/Subsystems Analysis.

operation, premature operation, and degraded or out-of-tolerance operation. Unique failure modes may be singularly inserted in this stage of the process. An example FMEA summary report for a hydraulic control surface actuator for the example FCS is presented in Figure 4.7.

Aircraft System	Subsystem Component	Location	Failure Mode	Effect on Subsystem	Effect of Degraded Subsystem on Aircraft	Aircraft Kill Category	Supporting References	Comments
Flt. Controls	Hyd. Act. #XXXX	Vert. Stab.	Jammed	Rudder Hardover	Balanced flight obtainable with cross-control; aircraft uncontrollable in PA config.	"B"; aircraft uncontrol-lable in landing configuration	#1,5,7	2,4
			Severed	Rudder Trails	Balanced flight obtainable with cross-control or differential engine power	---, aircraft can fly and land with other control surfaces functioning	#3	6

Figure 4.7. Example FMEA Summary Report - Hyd. Actuator

The actuator becomes a critical component for an attrition kill if it jams the control surface into a hard-over condition, but it is not a critical component if it allows the control surface to remain unjammed.

Another analysis procedure, the Fault Tree Analysis, employs a "top- down" approach [Ref. 5]. This approach differs from the FMEA in that it assumes an undesired event and systematically determines what failure or sequence of failures could cause the undesired outcome. A segment of an FTA for the example FCS is presented in Figure 4.8. The symbology utilized in the FTA analysis is common to logic systems and, as such, the FTA is often selected for its suitability with computational systems.

FCS failure modes that could result in aircraft attrition have been identified for the example FCS and are presented in Table III.

The FMEA and FTA related failure modes and effects but did not distinguish the possible cause(s) of the failure. The Damage Mode and Effects Analysis (DMEA) provides this essential relationship. In the DMEA, the component and subsystem failures are related to specific damage causing mechanisms and damage processes. Included in

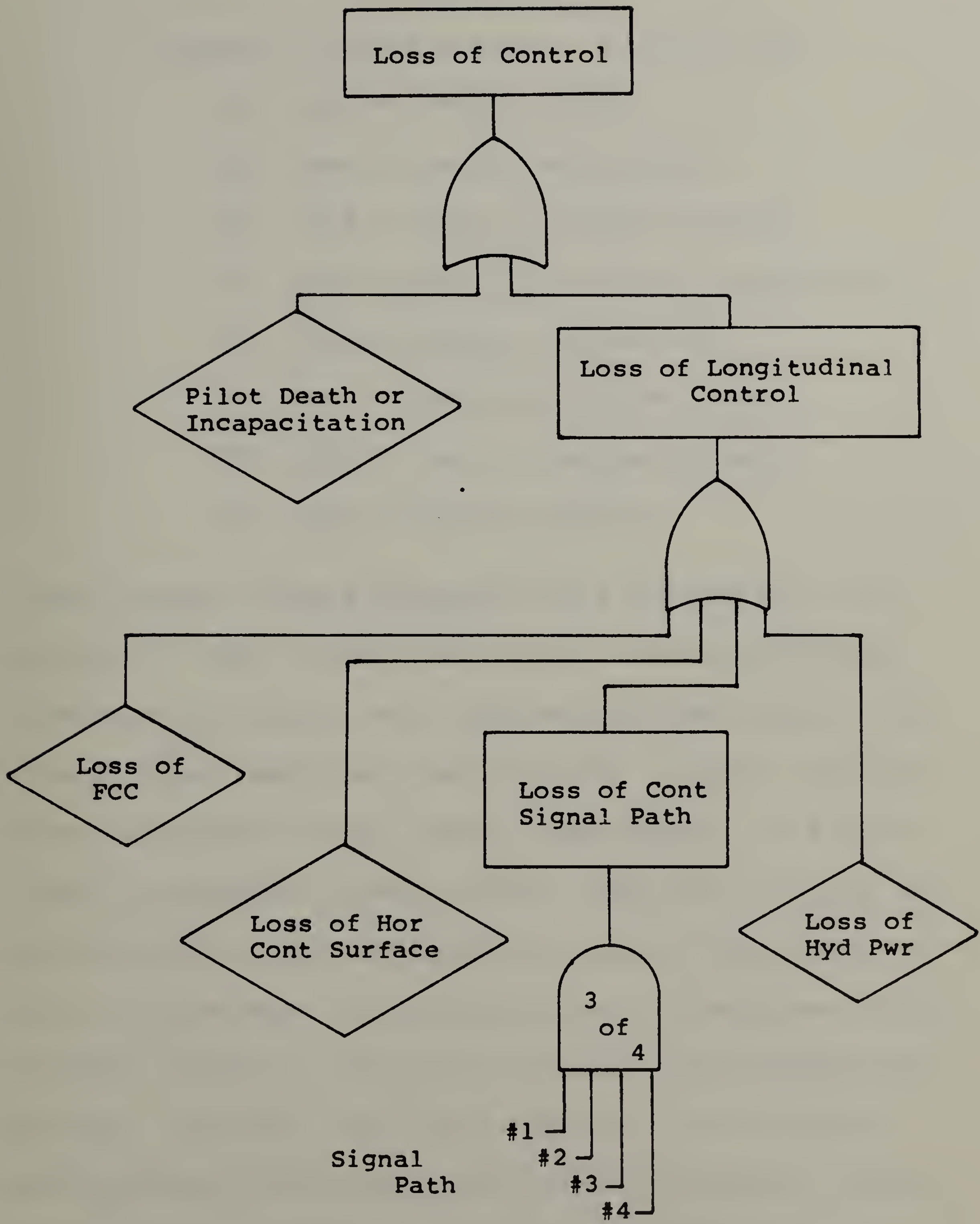


Figure 4.8. A Segment Of An FTA For The Example FCS.

TABLE III

Example FCS Failure Modes - Attrition Kill

(1) Loss of control inputs

(2) Loss of motion sensor data

(3) Loss of digital computer control

(4) Loss of electrical power to computer(s)

(5) Loss of control signal path

(6) Loss of hydraulic system power

(7) Loss of control surface actuator

(8) Loss of control surface

these primary damage mechanisms are projectiles and fragments, blast effects from high explosive warheads, incendiary particles, and High Energy Lasers (HEL). The damage these agents may cause includes severed electrical power distribution lines, sensor signal paths, and control signal transmission lines; jammed mechanical linkages and servoactuators; loss of hydraulic pressure and hydraulic fluid loss/leakage; fire (aggravated by petroleum based hydraulic fluid); HEL burn-through and high temperature heating or melting of FCS components, and certain electromagnetic incompatibilities with components, devices, cables, wiring, and connectors. Secondary damage mechanisms

resulting from the impact of the primary agents on the FCS include fire, explosion, spalling, structural deformation, sparks, and fluid leakage. The DMEA process evaluates cause and effect, and quantifies the likelihood of the outcome. Secondary damage causes, resulting from the primary damage mechanism or process, are included in the evaluation during this analysis phase. Detailed descriptions of the vulnerability assessment quantification process are presented in reference 1 and in MIL-STD-336-1 [Ref. 2].

Failure modes can be categorized and qualitatively aligned with the various damage causing devices or events. Figure 4.9 correllates the example FCS failure modes presented in Table III with common conventional weapons damage causing agents.

The next step in the vulnerability assessment process is the actual determination of the critical components for the selected kill level assessed. Distinguishing between redundant and non-redundant critical components is essential in this phase of the analysis. To clarify this important distinction, a set of components is defined to be redundant if the loss of one or more than one, but not all of the components, does not result in the loss

Failure/Damage Modes	Damage Mechanisms					
	Penetrator	Continuous Rod	Fragment	Blast	Fire	Radiation
Structural Failure Modes						
Area Removal	X	X	X	X	X	
Overpressure				X		
Thermal Degradation					X	X
Penetration	X	X	X			
Electrical Power System Failure Modes						
Line Severance	X	X	X	X	X	X
Grounding	X	X	X	X	X	X
Avionics System Failure Modes						
Failure to Operate	X	X	X	X	X	X
Degraded Operations	X	X	X	X	X	X
Hydraulic Power System Failure Modes						
Loss of Fluid	X	X	X	X	X	X
Loss of Pressure	X	X	X	X	X	X
Jammed Actuator	X	X	X	X	X	

Figure 4.9. FCS Failure Modes/Damage Causing Agents

of the essential function these components perform. If this distinction can not be made, the components are non-redundant. As an example, the quadruple control signal paths shown for the example FCS form a multiply redundant system because the essential function of providing a

continuous signal path is maintained even though one or more than one individual path may be rendered discontinuous.

Another distinction regarding redundancy must be made. The term "analytical redundancy" refers to a method whereby a computational algorithm is used to predict an end event or parameter. Then the prediction and a sensor derived measurement are compared, and subsequent action(s) taken. While not fitting the precise definition of redundancy, the computational results can be suitably used in lieu of the sensor output in certain circumstances.

The determination of the critical components and the presentation format are often presented in a "kill tree" or "kill expression." Referring to that portion of the kill tree shown in Figure 4.10, the physical relationship to a tree is apparent. The severance of sufficient trunk segments may result in the loss of the tree and in the case of the FCS, the loss of the aircraft.

Once identified, the critical components may be subject to various engineering redesigns to reduce their contribution to the vulnerability of the aircraft.

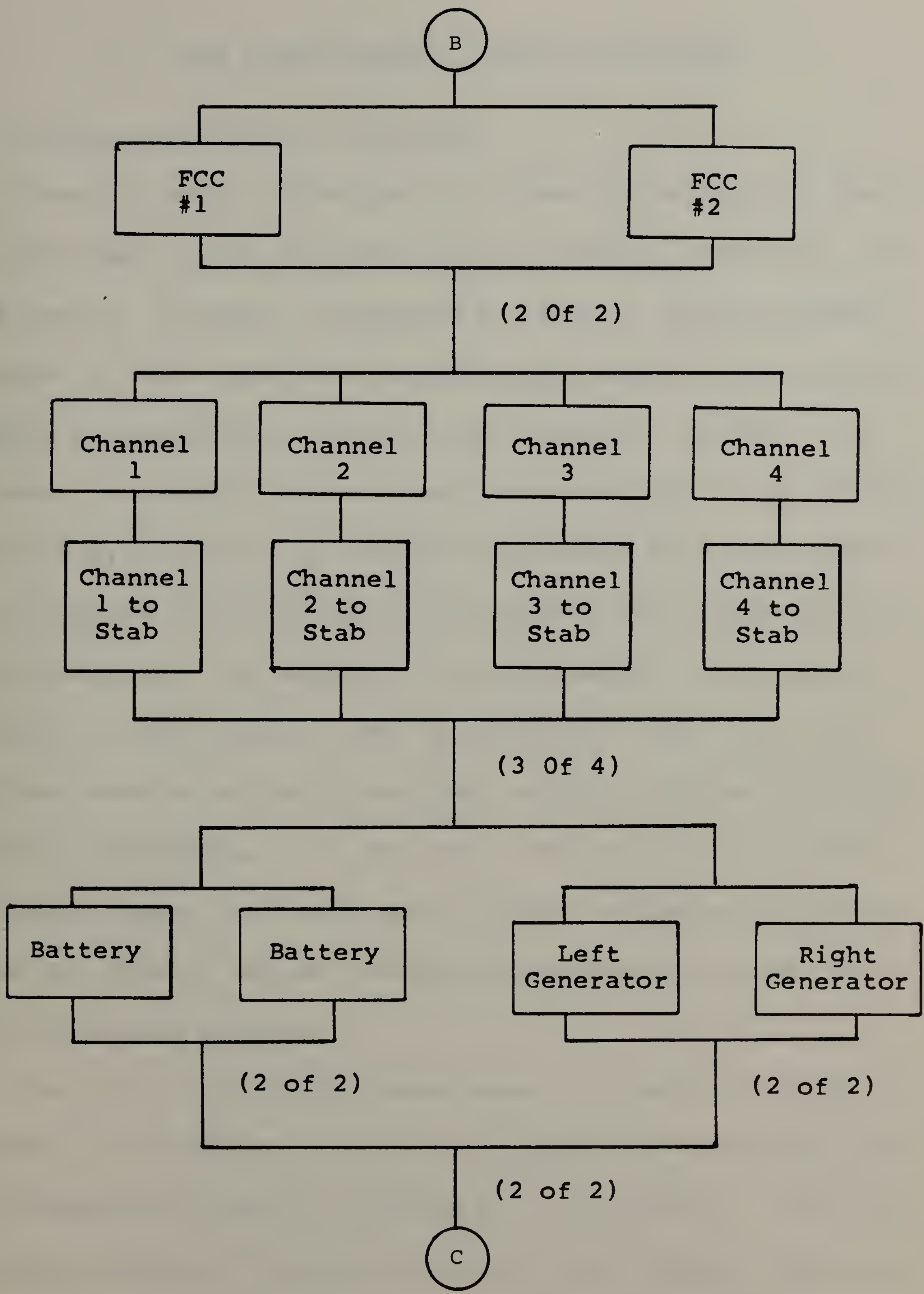
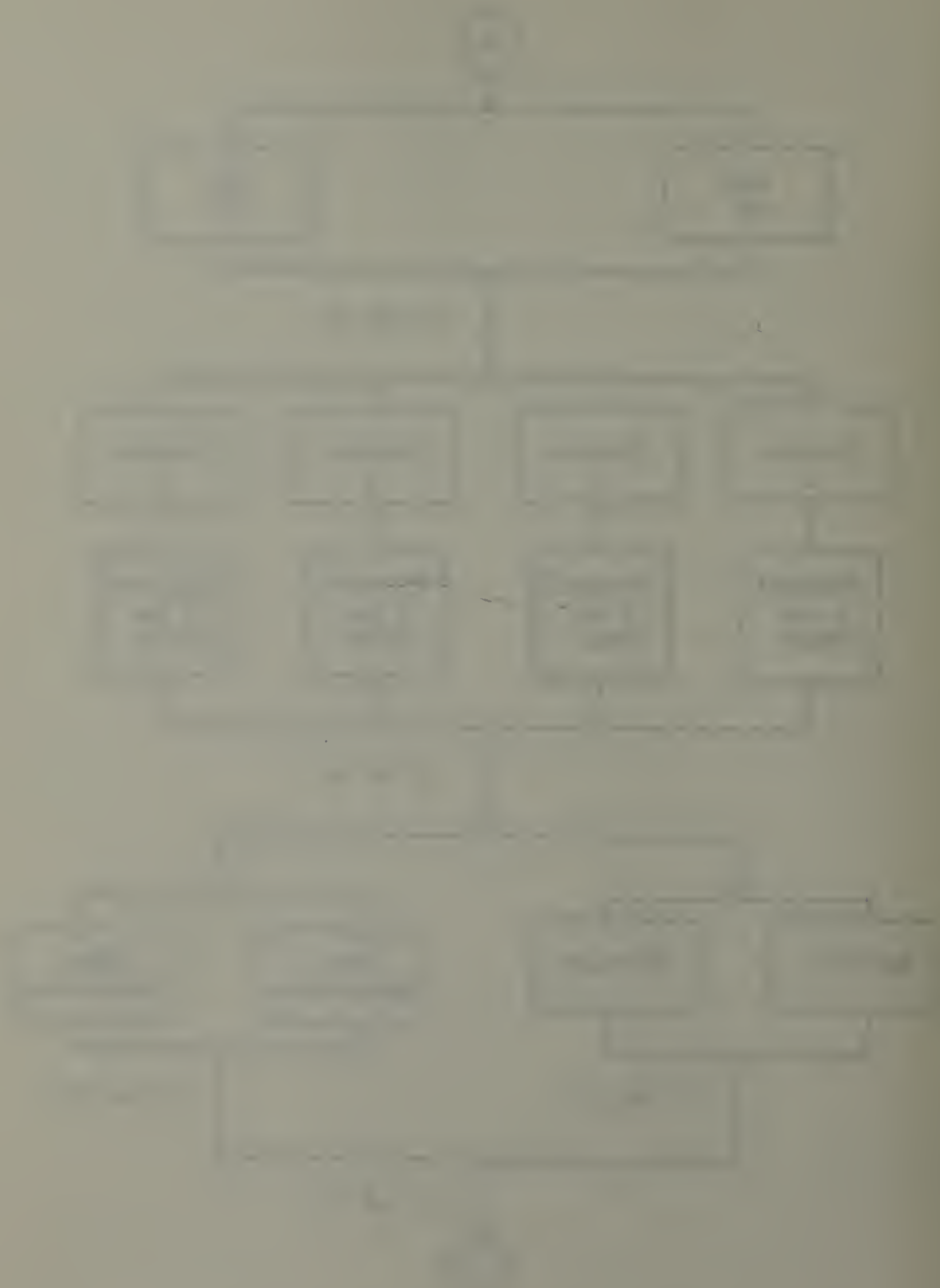


Figure 4.10. FCS Conventional Weapons Kill Tree



V. FCS SURVIVABILITY DESIGN GUIDELINES

A. GENERAL FCS DESIGN PRINCIPLES

General design principles to reduce vulnerability should be exercised to the fullest extent possible throughout the FCS design process. Commencing with the initial design phases, a full measure of consideration must be given to the combat survivability of the flight control system. Of course, the desire for increased survivability of the flight control system must be prudently balanced with the other requirements of reliability, maintainability, accessibility, repairability, and safety. Concurrently, the fullest measure of performance must be achieved, and all these factors must be suitably combined within stringent cost and weight constraints. In the end, the design of the FCS of military combat aircraft must include suitable protection from the primary damage causing mechanisms of conventional threat weapons systems.

The six survivability enhancement concepts developed in Chapter II (Table II, page 19) provide the foundation for the general FCS design principles. In general, the FCS design principles contain provision for component location and shielding to reduce potential damage risks; elimination

(via redesign) of high risk, single point failure components; component redundancy with adequate separation of redundant components to maintain the essential flight control function; and the incorporation of passive and active damage suppression devices and techniques to minimize the effects of incurred damage. A flight control system design that includes no single point kill possibilities should be considered a design goal.

B. SURVIVABILITY DESIGN GUIDELINES FOR FBW FCS

Specific survivability design guidelines applicable to the individual components and subsystems of a Fly-by-Wire Flight Control System have been formulated and are herein presented. The decision to incorporate any or all of the design guidelines must be made prudently and with sound engineering judgement.

1. Mechanical System Components

a) Flight Control Surface Panels

Where possible:

- Design control surface panels of lightweight composite materials which exhibit high strength-to-weight ratios and integral redundant load carrying capability for high ballistic damage tolerance.
- Incorporate smooth surface transitions to reduce aircraft signatures.
- Incorporate multiple surface panels on each control plane to provide redundant control surfaces for maximum reconfigurability.
- Utilize heat resistant surface material or

ablative materials to retard HEL burnthrough.

b) **Hinges/Control Linkages/Bearing Assemblies**

Where possible:

- Design components to be jam-free.
- Utilize self-aligning bearings (e.g. tri-pivot bearings) to minimize misalignment and jamming due to control rod, actuator arm, or control surface panel deformation.
- Minimize the length of mechanical control linkages to reduce the probability of deformation or distortion.
- Utilize ballistically damage tolerant composite materials for control rods and torque tubes.
- Design fairleads, bellcranks, and idler assemblies to allow a measure of functional performance if damaged.
- Install primary drive motors, control linkages, interconnecting devices, and bearing assemblies in close proximity to primary structural members to take advantage of the shielding afforded by the primary structure.
- Ensure that that all control surfaces are fitted with a "trail safe" positioning device to prevent hardover conditions in the event of the loss of the drive linkage.

c) **Servoactuators**

Where possible:

- Design all servoactuators with redundant power sources (e.g. dual cylinder actuators).
- Design actuator pistons of frangible or malleable materials to minimize the possibility of jamming.
- Design actuator barrel assemblies of high strength steel for high ballistic resistance (e.g. Electro-Slag Remelt (ESR) Steel).
- Design the actuator outer-barrel assemblies to prevent crack propogation.
- Install servoactuators in close proximity to primary structural members for maximum shielding.
- Install rate and position feedback linkages in close proximity to the servoactuator assembly for maximum shielding.

- Utilize integral reservoir, pump, and electric power packages when possible (e.g. Integrated Actuator Packages (IAP)).
- Incorporate metallic seals in place of polymeric seals for HEL protection.
- Coat actuator housings with high temperature resistant or ablative materials for HEL burnthrough protection.
- Incorporate high strength ablative armor in areas of critical components.
- Incorporate very high signal-to-noise ratio servovalves for increased EMI tolerance.

2. <u>Hydraulic Power Systems</u>

a) **Fluid Pressure Generation Subsystems**

Where possible:

- Design hydraulic power sources to be single or double redundant (e.g. separate dual or triple hydraulic power sources).
- Physically separate hydraulic power sources as much as possible to reduce the single shot kill probability of a multiple hydraulic system.
- Install power sources in close proximity to main structural members to provide maximum shielding.
- Incorporate high temperature resistant or ablative material coatings on hydraulic pump cases to increase HEL burnthrough tolerance.

b) **Fluid Pressure Distribution Subsystems**

Where possible:

- Design fluid pressure distribution systems of high strength, high temperature tolerant steel lines.
- Incorporate single or double redundant distribution lines on each separate fluid pressure system.
- Incorporate flow sensors, check valves, and switching circuits to bypass damaged segments of distribution lines.
- Incorporate reservoir level sensing devices to isolate damaged distribution lines to prevent fluid loss.
- Install distribution lines in close proximity

to main structural members to maximize shielding.

- Utilize very high pressure (i.e. 4000-6000 psi) systems to reduce presented area.
- Utilize high temperature resistant synthetic-based hydraulic fluid to reduce or eliminate fire potential.

3. Electronic System Components

a) Flight Control Avionics Components

Where possible:

- Design all primary FBW FCS avionics components with multiple redundancy (e.g. multiple LVDT control input sensors on each control axis input, and multiple digital flight control computers).
- Separate redundant avionics components to minimize single shot kill probabilities.
- Design all avionics component cases of high strength steel for maximum ballistic resistance.
- Coat all avionics component cases with high temperature resistant or ablative materials for maximum HEL burnthrough protection.
- Design shock mounts for internal and external components to withstand vibration and weapons induced shock loads.
- Install avionics components in close proximity to primary structural members for maximum shielding.
- Incorporate high temperature resistant or ablative armor in areas surrounding critical components.
- Design electronic components with suitable particulate, vapor, and moisture protection.

b) Electronic Circuit Design

Where possible:

- Design input/output circuits of very high Signal-to-Noise (S/N) ratio components for maximum EMI protection.
- Minimize capacitive and inductive cross-coupling in electronic circuits.
- Incorporate suitable self-protect, energy

dissipative circuits to provide lightning and EMI/EMP protection (e.g. fusible links, filters,or spark-gap devices).

- Provide separate and redundant analog channels, with separate voting logic, as a backup to the digital controller.

c) **Signal Transmission Paths**

Where possible:

- Design single or double redundant signal paths between each component or element in a signal path.
- Provide suitable separation between redundant signal transmission lines to reduce the single shot kill probability.
- Route signal transmission lines in close proximity to primary structural members for maximum shielding.
- Provide adequate electromagnetic shielding to reduce EMI.
- Utilize high temperature resistant wire covering to maximize thermal/fire protection and to minimize HEL burnthrough.

d) **External Sensors/Ancillary Subsystems**

Where possible:

- Design multiple redundant external sensors and ancillary subsystems (e.g. Air Data Computers, and Angle of Attack systems).
- Incorporate high temperature resistant or ablative material armor for thermal, HEL and ballistic damage tolerance.
- Provide separate, redundant motion and rate sensors on each of the three aircraft axes.
- Mount sensors to primary structural members for maximum shielding.
- Provide analytically redundant sensory outputs for use as checks, and as potential back-ups.
- Provide adequate built-in test circuits with suitable failure warning indications.
- Incorporate separate and widely displaced sensor signal transmission paths.

e) **Pilot Control Inputs**

Where possible:

- Design redundant control stick and rudder input sensor contacts.
- Utilize sequenced voting logic and multiplex control commands to each of the central processing units of the flight control computer(s).
- Incorporate separate and widely displaced input command signal transmission paths.

4. Electrical Power System

a) **Electrical Power Generation**

Where possible:

- Design electrical power generation systems to be multiply redundant (e.g. dual generators, each with single generator capability).
- Incorporate multiply redundant AC/DC conversion elements.
- Utilize automatic/manual or manually activated ram air turbine emergency generators, with separate AC/DC conversion elements.
- Design battery back-up systems.

b) **Electrical Power Distribution**

Where possible:

- Design electrical bus distribution systems for "cross-over" transient-free operation.
- Incorporate redundant control signal/power wiring to IAP (if utilized).

5. Environmental Control System

Where possible:

- Design separate and redundant a priori distributed heating and cooling, pressurization, and volumetric flow systems to critical components (e.g. flight control computer(s)).
- Incorporate fail-safe temperature, pressure, and volume flow sensors (i.e. a safe operating condition is maintained should a failure occur).

- Provide ram air emergency cooling to heat sensitive components.

- Design adequate particulate, vapor, and moisture control devices in primary and emergency cooling and pressurization systems.

VI. SUMMARY AND RECOMMENDATIONS

A. SUMMARY

In summary, it has been the author's desire to present in a single document a clear-cut set of guidelines for the development of aircraft flight control systems with specific emphasis on increasing the combat survivability of aircraft equipped with FBW flight control systems. The material presented and the guidelines delineated have resulted in a document that is as complete and concise as any single source document can be when dealing with a fast-paced, highly complex technical subject. This document should therefore be viewed as a dynamic tool that reflects a continuous chain of ongoing thoughts and actions to constantly update and strengthen the quality, capability and survivability of the combat systems of our Armed Forces.

B. RECOMMENDATIONS FOR FUTURE ACTIONS

Enhanced survivability alternatives achievable through digital FBW FCS technology should be investigated fully. One such survivability enhancement alternative, achievable through digital technology, is a "self-healing", reconfigurable aircraft flight control system.

Consider for a moment that you are the pilot of an aircraft that has just been hit by enemy ground-fire. You feel the dull thud as the enemy projectile impacts your aircraft's aft fuselage area and now you sense the aircraft beginning to pitch and roll without command. Your survival instinct tells you to try every possible combination of stick and rudder input to counter the out-of-control aircraft motion. Nothing seems to correct the situation.......your final thought prior to ejecting from your stricken craft is "if only......"

This hypothetical example is but one of many possible combat related incidents that might be resolved in another way through the use of digital technology. Consider the possibilities afforded by digital technology in regaining control over a combat damaged aircraft as in the aforementioned example. With one of the horizontal stabilators gone, an alternate combination of primary and secondary control surfaces might be commanded by the computer to return the aircraft to controlled flight. This proposed survivability enhancement alternative could be obtained with minimal additions to present digital fly-by-wire flight control configurations. The addition of

a sensor suite, to detect and identify damaged flight control components, and a computational algorithm to reconfigure the aircraft control surfaces, similar in nature to that used in artificially intelligent robot devices, are all that is required. Without question, successfull achievement of such an adventuresome engineering task would require a dedicated effort. Outlined in the following, is a plan to accomplish such a project. It is the author's opinion that sincere thought and consideration should be given to such an undertaking in the near term.

A plan to develop an artificially intelligent, reconfigurable flight control system would require detailed engineering analyses of the following areas:

- Computational analysis, and wind tunnel determination of aerodynamic lift, drag and moment coefficients on simulated combat damaged aircraft models (e.g. model testing of missing, jammed or trailing-free control surfaces in single and multiple combinations).

- Development of control surface reconfigurability alternatives.

- Development of suitable sensors to detect the various levels and modes of combat damage.

- Development of a sequenced logic or built-in test routine to verify flight control system configuration and status.

It is the author's opinion that the fundamental technology and expertise are present within the military-industrial community to achieve the aforementioned

survivability enhancement alternative at low technological risk and low cost. It is hoped that tomorrow's history does not show the way to progress in aircraft survivability.

LIST OF REFERENCES

1. Ball, R.E., *The Fundamentals of Aircraft Combat Survivability Analysis and Design*, Naval Postgraduate School, 1983.

2. Department of Defense Military Standard, MIL-STD-336-1, *Survivability, Aircraft, Nonnuclear, General Criteria-Volume 1*, 25 October, 1982.

3. Department of Defense Military Specification, MIL-STD-8785C, *Military Specification, Flying Qualities of Piloted Airplanes*, 5 November 1980.

4. Department of Defense Military Standard, MIL-STD-785, *Reliability Program for Systems and Equipment Development and Production*, 15 September 1980.

5. Roland, H.E. and Moriarity, B., *Systems Safety Engineering and Management*, John Wiley and Sons, 1983.

BIBLIOGRAPHY

American Defense Preparedness Association, Proceedings Of The Symposium On Vulnerability And Survivability, Volume I - Unclassified, Naval Amphibious Base Coronado, 21-23 October 1975.

Boudreau, J. A. and Berman, H. L., Dispersed And Reconfigurable Digital Flight Control System Study, Volume I, Grumman Aerospace Corporation/Air Force Flight Dynamics Laboratory, AFFDL-TR-79-3125, Vol. 1, December 1979.

Cunningham, T. B., "Failure Management Techniques For High Survivability," AGARD Lecture Series No. 109 - Fault Tolerance Design And Redundancy Management Techniques, AGARD-LS-109, October 1980.

Department Of The Navy, Military Specification , SD-24L Volume 1 - Fixed Wing Aircraft, General Specification For Design and Construction of Aircraft Weapons Systems, 2 June 1982.

Graham, K. D., et. al., Aircraft Flight Control Survivability Through The Use of On-board Digital Computers, Joint Technical Coordinating Group For Aircraft Survivability, JTCG/AS-77-T-002 May 1980.

Hooker, D. S., et. al., Definition Study For An Advanced Fighter Digital Flight Control System, McDonnell Aircraft Company/Air Force Flight Dynamics Laboratory, AFFDL-TR-75-59, June 1975.

Joint Technical Coordinating Group/Aircraft Survivability, The Proceedings Of The Aircraft Survivability Symposium: A State Of The Art Update, Volume I - Unclassified Papers, Naval Postgraduate School, 13-15 July 1976.

Konar, A. F., et. al., Digital Flight Control System For Tactical Fighters, Honeywell Inc./Air Force Flight Dynamics Laboratory, AFFDL-TR-74-69, July 1974.

Larimer, S. J., Capt., USAF and Maher, S. L., 1LT, USAF, A Continuously Reconfiguring Multi-Microprocessor Flight Control System, Air Force Wright Aeronautical Laboratories, AFWAL-TR-81-3070, May 1981.

Martin, D. J., Dissimilar Redundancy For Fly-By-Wire Secondary Flight Controls, 1981 Advanced Flight Controls Symposium, USAF Academy, 5-7 August 1981.

McGough, J., et. al., Digital Flight Control System Redundancy Study, Bendix Corporation/Air Force Flight Dynamics Laboratory, AFFDL-TR-74-83, July 1974.

Miller, F. L. and Emfinger, J. E., Fly-By-Wire Techniques, Sperry Phoenix Company/Air Force Flight Dynamics Laboratory, AFFDL-TR-67-53, July 1967.

Pullen, K. A., Effects Of Redundancy On Survival Of Critical Avionics Equipment, Ballistic Research Laboratories, BRL-MR-2266, January 1973.

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